

# Degeneracies at a $\beta$ -Beam and a Super-Beam Facility

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The presence of degeneracies can considerably worsen the measure of the neutrino oscillation parameters  $\theta_{13}$  and  $\delta$ . We study the physics reach of a specific “CERN” setup, using a standard  $\beta$ -Beam and Super-Beam facility. These facilities have a similar sensitivity in both parameters. Their combination does not provide any dramatic improvement as expected due to their almost identical L/E ratio. We analyse if adding the correspondent disappearance channels can help in reducing the effect of degeneracies in the  $(\theta_{13}, \delta)$  measure.

## 1. Introduction

The best way to simultaneously measure  $(\theta_{13}, \delta)$  is the (golden)  $\nu_e \rightarrow \nu_\mu$  appearance channel [1] (and its T and CP conjugate ones). Unfortunately this measure is severely affected by the presence of an eightfold degeneracy [2]. Various methods have been considered to get rid of degeneracies: spectral analysis, combination of experiments and/or different channels. In principle, the eightfold degeneracy can be completely solved if a sufficient large set of independent informations is added. At the cost, of course, of increasing the number of detectors and/or beams and, consequently, budget needs.

We try to understand here if the effect of degeneracies can be reduced adding informations from both the appearance and the disappearance channels at a single experiment. We consider as a reference two proposed CERN-based facilities: the standard- $\gamma$   $\beta$ -Beam [3] and the 4 MWatt SPL Super-Beam [4]. Both neutrino beams are directed from CERN toward a 1 Mton water Cerenkov detector placed in the underground Fréjus laboratory. The considered baseline is  $L = 130$  km. The average neutrino energy for both beams is  $\approx 250$  MeV.

The eightfold degeneracy for these two facilities has been comprehensively studied in [5,6] and we

refer to those papers for all the technical details and a complete set of bibliographic references.

## 2. $\beta$ -Beam Appearance and Disappearance Channels

The considered  $\beta$ -Beam setup consists of a  $\bar{\nu}_e$ -beam produced by the decay of  ${}^6\text{He}$  ions boosted at  $\gamma = 60$  and of a  $\nu_e$ -beam produced in the decay of  ${}^{18}\text{Ne}$  ions boosted at  $\gamma = 100$ . The average neutrino energies of the  $\nu_e, \bar{\nu}_e$  beams are 0.37 GeV and 0.23 GeV, respectively.

The measurement of  $(\theta_{13}, \delta)$  at this facility has been already actively discussed in the literature [7,5]. In Fig. 1 we plot our results for  $\theta_{13} = 8^\circ$  and two different CP phases:  $\delta = 45^\circ$  and  $-90^\circ$ . The input value used in the fit is always shown as a filled black box. Throughout the paper we are using the following reference values for the atmospheric and solar parameters:  $\Delta m_{atm}^2 = 2.5 \times 10^{-3} \text{ eV}^2$ ,  $\theta_{23} = 40^\circ$ ,  $\theta_{12} = 33^\circ$  and  $\Delta m_{sol}^2 = 8.2 \times 10^{-5} \text{ eV}^2$ . The 90% CL contours for each of the degenerate solutions are depicted in the plot assuming a 5% systematic error and are fully explained in the caption. In Fig. 1 it can be seen the dramatic impact that degeneracies have in the precision of the measure of  $(\theta_{13}, \delta)$ : (1) the error in the  $\theta_{13}$  measurement is increased by a factor four (two) for large (small) values of  $\theta_{13}$  [8]. The presence of degeneracies has a small impact on the ultimate  $\theta_{13}$  sensitivity; (2) the error in the  $\delta$  measurement grows in a signif-

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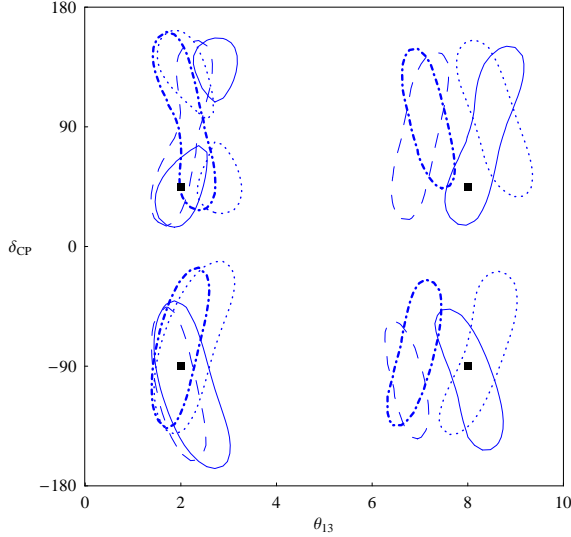


Figure 1. 90% CL contours in the  $(\theta_{13}, \delta)$  plane using the appearance channel after a 10 years run at the considered  $\beta$ -Beam for  $\theta_{13} = 2^\circ, 8^\circ$ , and  $\delta = 45^\circ, -90^\circ$ . A 5% systematic error is assumed. Continuous, dotted, dashed and dot-dashed lines stand respectively for the intrinsic, sign, octant and mixed degeneracy.

icant way in presence of the clones, almost spanning half of the parameter space for small values of  $\theta_{13}$ . These facts are well understood: being the standard  $\beta$ -Beam a (short distance) counting experiment there are not enough independent informations to cancel any of the degeneracies.

At the  $\beta$ -Beam the  $\nu_e$  disappearance channel is also available. The  $\nu_e$  disappearance probability does not depend on the CP violating phase  $\delta$  and the atmospheric mixing angle  $\theta_{23}$ . Thus, the  $\theta_{13}$  measurement, in this channel, is not affected by the intrinsic, octant and mixed ambiguities.

In Fig. 2 we present the  $\nu_e$  disappearance measure for three different systematic errors, namely 0% (“theoretical-unrealistic” scenario), 2% (“optimistic” scenario) and 5% (“pessimistic” scenario). The 0% systematic line represent the ultimate (error free) reach of this experiment.

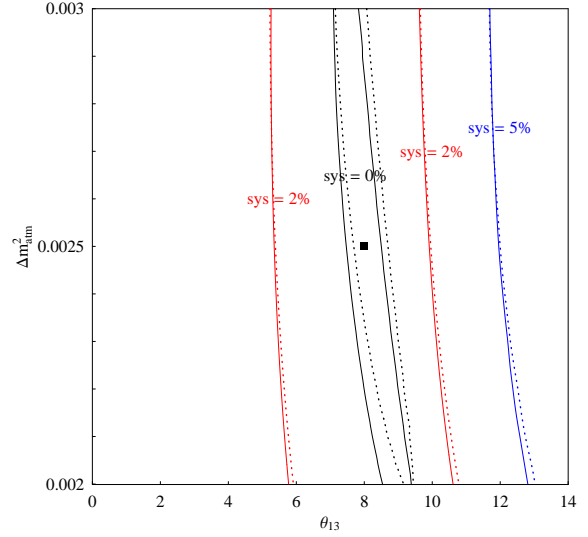


Figure 2. 90% CL contours in the  $(\theta_{13}, \Delta m_{atm}^2)$  plane using the disappearance channel after a 10 years run at the considered  $\beta$ -Beam for  $\theta_{13} = 8^\circ$ . Three different values of the systematic errors have been considered: 0%, 2% and 5%. Continuous (dotted) lines stand for the true solution (sign degeneracy).

The 2% and 5% lines will cover the optimistic and pessimistic feelings about future improvements in understanding a Mton water detector. The 90% CL contours in the  $(\theta_{13}, \Delta m_{atm}^2)$  plane are shown for the input values  $\theta_{13} = 8^\circ$  and  $\Delta m_{atm}^2 = 2.5 \times 10^{-3} \text{ eV}^2$ . The  $\nu_e$  disappearance channel is only slightly sensitive to the sign clone. In fact, the dependence on the sign of the atmospheric mass difference arises only at  $\mathcal{O}(\theta_{13}^2)$ . As a consequence the  $\nu_e$  disappearance channel is an almost “clone-free” environment for the  $\beta$ -Beam, as it is for reactors experiments. However, even in the case of an optimistic 2% systematic error, no improvement is obtained adding the disappearance channel informations to the results of Fig. 1 for the appearance channel. The resulting 90% CL contours practically coincide with the previous ones, and for this reason we do not consider

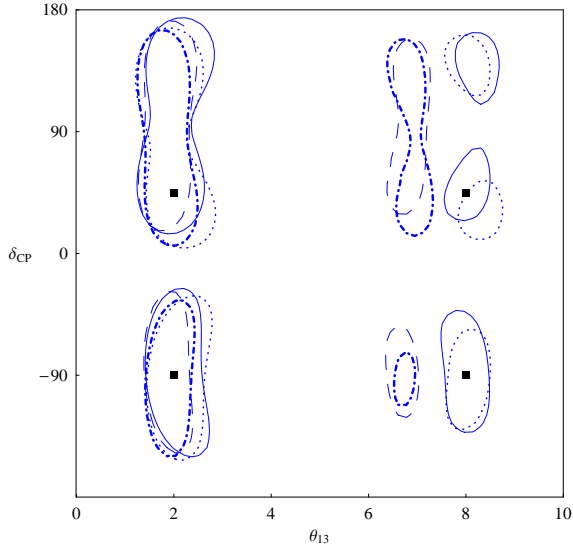


Figure 3. 90% CL contours using the appearance channel after a 2+8 years run at the Super-Beam for two different values of  $\theta_{13} = 8^\circ$ , and two values of  $\delta$ :  $45^\circ$  and  $-90^\circ$ . A 5% systematic error is assumed. The legend is the same as in Fig. 1.

to present them in a separate figure. The  $\theta_{13}$  indetermination coming from the clone presence in the appearance channel is smaller than the disappearance error itself. Only considering an unrealistic 0% systematics the disappearance channel starts to be useful in eliminating clones.

### 3. Super-Beam Appearance and Disappearance Channels

The considered Super-Beam setup is a conventional neutrino beam based on the 4 MWatt CERN SPL 2.2 GeV proton driver [4]. The average neutrino energies of the  $\nu_\mu$ ,  $\bar{\nu}_\mu$  beams are 0.27 GeV and 0.25 GeV, respectively. The possibility to measure  $(\theta_{13}, \delta)$  at a standard Super-Beam facility has been already widely discussed [9,5].

In Fig. 3 we plot our results for  $\theta_{13} = 8^\circ$  and two different CP phases:  $\delta = 45^\circ$  and  $-90^\circ$ . The input value used in the fit is shown as a filled black

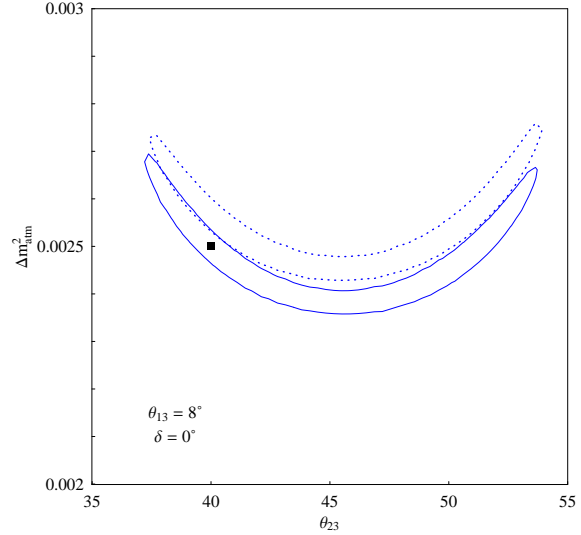


Figure 4. 90% CL contours in the  $(\theta_{23}, \Delta m_{atm}^2)$  plane using the disappearance channel after a 2+8 years run at the Super-Beam for  $\theta_{23} = 40^\circ$ . A 2% systematic error is assumed. Continuous (dotted) lines stand for true (wrong) atmospheric mass sign assignment.

box. The 90% CL contours for each of the degenerate solutions are depicted in the plot assuming a 5% systematic error and are explained in the caption. As it appears from comparison of Fig. 3 with Fig. 1, the “figures of merit” of a standard  $\beta$ -Beam and the SPL Super-Beam are very similar. Also the Super-Beam appearance channel is severely affected by proliferation of clones. The precision in measuring  $(\theta_{13}, \delta)$  is practically identical in the two cases. This is well explained by the comparable statistics in the golden channel ( $\nu_e \rightarrow \nu_\mu$  vs  $\bar{\nu}_\mu \rightarrow \nu_e$ ) and an almost equal  $L/E$  ratio for the two experiments. There is no real synergy between these two setups and the only effect in summing these two experiments (concerning the  $(\theta_{13}, \delta)$  measure) is to double the statistics.

Nevertheless, the great advantage of the Super-Beam facility compared with the  $\beta$ -Beam one is the possibility to measure directly the atmo-

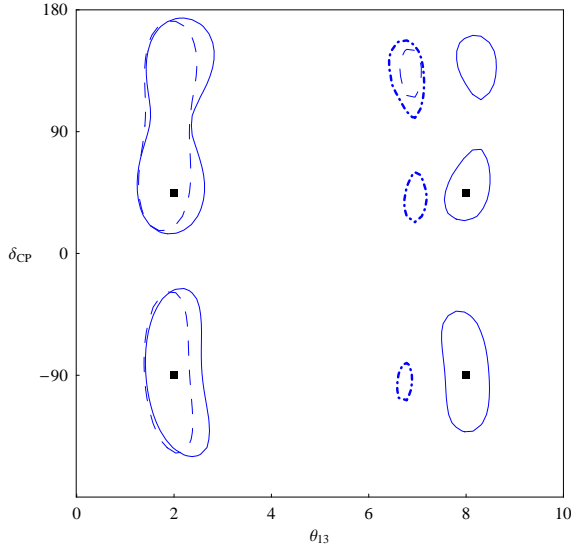


Figure 5. 90% CL contours using the appearance and the disappearance channels after a 2+8 years run at the Super-Beam, for  $\theta_{13} = 2^\circ, 8^\circ$  and  $\delta = 45^\circ, -90^\circ$ . A 5% (2%) systematic error is assumed for the appearance (disappearance) channel. The legend is the same as in Fig. 1.

spheric parameters using the  $\nu_\mu$  disappearance channel reducing, in particular, the atmospheric mass difference error to less than 10%. In Fig. 4 we show the measure of  $(\theta_{23}, \Delta m_{atm}^2)$  at the SPL Super-Beam with a 2% systematic error for a non-maximal atmospheric mixing,  $\theta_{23} = 40^\circ$  and  $\Delta m_{atm}^2 = 2.5 \times 10^{-3} \text{ eV}^2$ . The continuous (dotted) contour represents the fit to the right (wrong) choice of the sign of the atmospheric mass difference. Since we plot the results in the full  $\theta_{23} \in [35^\circ - 55^\circ]$  parameter space, the octant and mixed clones are automatically taken into account and do not appear as separate regions (within the considered errors). As one can notice the sign ambiguity implies that the errors on the atmospheric mass difference are roughly doubled with respect to what expected in the absence of degeneracies. The presence of degeneracies in the  $\nu_\mu$  disappearance channel can be easily

understood looking at the the  $\nu_\mu \rightarrow \nu_\mu$  vacuum oscillation probability expanded to the second order  $\theta_{13}$  and  $(\Delta m_{sol}^2 L/E)$  (see for example [10,6]).

In Fig. 5 we present the simultaneous measurement of  $(\theta_{13}, \delta)$  using both the appearance (with a 5% systematic error) and the disappearance (with a 2% systematic error) channels at the Super-Beam. Contrary to the  $\beta$ -Beam case, the disappearance Super-Beam channel introduces in the fit significant changes. Notably enough, the sign clone has disappeared in any case considered. This is not a surprise as these fits are performed at a fixed  $\Delta m_{atm}^2$ : since in the disappearance channel the sign clone manifests itself at a larger value of  $\Delta m_{atm}^2$  (see Fig. 4), in the combination with the appearance channel the tension between the two suffices to remove the unwanted clone in the  $(\theta_{13}, \delta)$  plane. Notice, moreover, that in some cases the octant clone is considerably reduced or even solved, due to the octant-asymmetric contributions in the  $\nu_\mu$  disappearance probability. Nonetheless, this does not mean that thanks to the combination of the appearance and the disappearance channels we are indeed able to measure the sign of the atmospheric mass difference. The mixed clones are generally still present for large values of  $\theta_{13}$ , thus preventing us from measuring the atmospheric mass difference sign if the  $\theta_{23}$ -octant is not known at the time the experiment takes place. It is clear that these results should be confirmed by a complete multi-dimensional analysis is underway.

#### 4. Conclusions

We have tried to understand the impact of disappearance measurements on the  $(\theta_{13}, \delta)$  eight-fold degeneracy for the standard- $\gamma$   $\beta$ -Beam and the SPL Super-Beam. We presented a complete analysis of degenerations in the  $\nu_e$  and  $\nu_\mu$  disappearance channels: the  $\nu_e$  disappearance is affected only by a twofold degeneracy, since the  $\nu_e$  probability does not depend on  $\delta$  and  $\theta_{23}$ . The  $\nu_\mu$  disappearance is affected by a fourfold-degeneracy. The inclusion of degeneracies almost double the error on the measure of  $\Delta m_{atm}^2$ .

The standard- $\gamma$   $\beta$ -Beam setup looks somewhat limited, being the neutrino energy too low for us-

ing energy resolution techniques and the combination with the  $\nu_e$  disappearance, potentially of interest, is in practice useless once a realistic systematic error is taken into account. The  $\beta$ -Beam idea should be certainly pursued further, but using for example higher  $\gamma$  options, where should be possible to take advantage of energy resolution and, possibly, the silver channel.

The SPL Super-Beam appearance channel is also severely affected by degeneracies. However, in this case the complementarity between the appearance and disappearance channels can be fully exploited even when a realistic systematic error is taken into account. In particular, the sign ambiguity can be strongly reduced as the disappearance sign clone is located at a different  $\Delta m_{atm}^2$ .

## REFERENCES

1. A. Cervera *et al.*, Nucl. Phys. B **579** (2000) 17 [Erratum-ibid. B **593** (2001) 731].
2. G. L. Fogli and E. Lisi, Phys. Rev. D **54** (1996) 3667; J. Burguet-Castell *et al.*, Nucl. Phys. B **608** (2001); H. Minakata and H. Nunokawa, JHEP **0110** (2001) 001; V. Barger, D. Marfatia and K. Whisnant, Phys. Rev. D **65** (2002) 073023.
3. P. Zucchelli, Phys. Lett. B **532** (2002) 166.
4. J. J. Gomez-Cadenas *et al.* arXiv:hep-ph/0105297.
5. A. Donini *et al.*, arXiv:hep-ph/0406132.
6. A. Donini *et al.*, arXiv:hep-ph/0411402.
7. M. Apollonio *et al.*, arXiv:hep-ph/0210192; M. Mezzetto, J. Phys. G **29** (2003) 1771; A. Blondel *et al.*, CERN-2004-002; M. Mezzetto, arXiv:hep-ex/0410083.
8. A. Donini *et al.*, JHEP **0406**, 011 (2004).
9. See for example P. Huber, M. Lindner and W. Winter, Nucl. Phys. B **645** (2002) 3, and references therein.
10. E. K. Akhmedov *et al.*, JHEP **0404** (2004) 078 [arXiv:hep-ph/0402175].